



Pugh, JR., Buss, IJ., Nash, GR., Ashley, T., Krier, A., Cryan, MJ., & Rarity, JG. (2007). FDTD modelling of mid infrared disk lasers. In *9th International Conference on Transparent Optical Networks, 2007 (ICTON '07) Rome, Italy* (Vol. 4, pp. 208 - 211). Institute of Electrical and Electronics Engineers (IEEE).
<https://doi.org/10.1109/ICTON.2007.4296380>

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Link to published version (if available):
[10.1109/ICTON.2007.4296380](https://doi.org/10.1109/ICTON.2007.4296380)

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FDTD Modelling of Mid Infrared Disk Lasers

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ABSTRACT

This paper presents 2D FDTD modelling of a disk resonator that could be used as a disk laser. Results are shown for mode spacing and good agreement with a simple Whispering Gallery Mode model is observed. The influence of direct coupled waveguides on modal behaviour is studied and a large reduction in cavity Q is observed.

Keywords: Mid-Infrared Laser, disk laser, FDTD modelling.

1. INTRODUCTION

Mid-Infrared (2–5 μm) emitting lasers have the common problem of a limited operating temperature. Many groups are working on different techniques to realise some of the potential applications of a 2–5 μm laser operating at room temperature. These include military counter measures, range finding, line of sight communications, medical diagnostics and industrial process control. Perhaps the most suited application of mid-IR lasers lies in gas detection [1]. Figure 1 shows the strong absorption encountered by many pollutant gases within the mid-IR wavelength region.

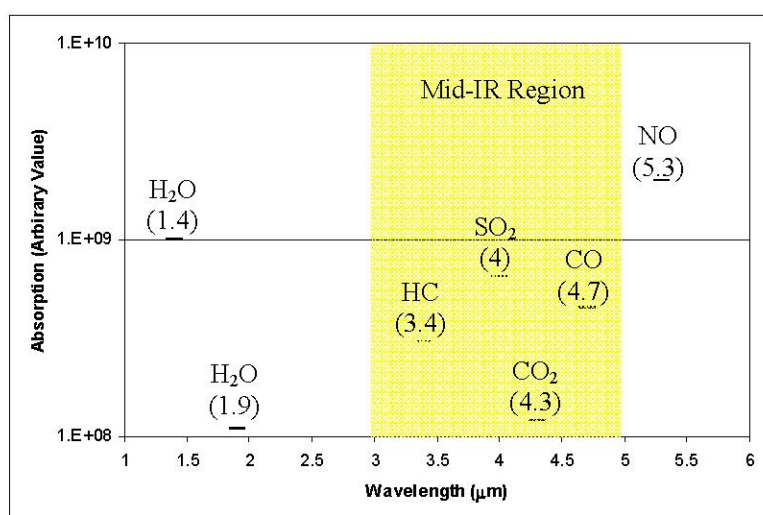


Figure 1. Spectroscopic survey of line strengths of important atmospheric trace gases and toxic pollutants in the 3–5 μm infrared region. [2].

Fundamentally, mid-IR lasers based on narrow gap semiconductors are subject to strong nonradiative recombination. Both Auger and Shockley-Reed-Hall recombination processes can limit their quantum efficiency, reduce net gain and prevent continuous room-temperature operation [3]. Here we report on results from a mid-IR disk resonator simulation which supports a whispering gallery mode (WGM) propagating around the inside edge of the structure [4]. After repeated total internal reflections at the curved boundary, the electromagnetic field closes in on itself giving rise to resonances. A high Q-factor is achievable in WGM resonators as no cleaved facets are necessary to create the cavity. This could lead to the possibility of making a working room temperature laser even when the gain in the active region is small. This paper investigates the influence of the way in which light is coupled into or out of such a disk resonator, with the aim of maximising output emission whilst maintaining high Q resonances. Initially directly coupled structures are studied, side coupled waveguides will be the subject of future work.

2. SIMULATION PROCEDURES

This paper reports results obtained from the Finite-difference time-domain (FDTD) method based on Yee's seminal paper in 1966 [5]. Here, an in-house 3D FDTD code which has been developed over many years is used [6]. Maxwell's Equations are discretized in both time and space coordinates, and in Yee's basic algorithm each grid node contains 3 E-field and 3 H-field components. Both the spatial positions as well as the temporal update of these components are offset and the equations are solved using a leap-frog-in-time technique. There are many advantages to this method; it is a rigorous algorithm that can handle dispersive material including metals, and as it is a time-domain method one simulation can give results over a broad frequency range.

For accurate results the FDTD mesh should be less than $\lambda_g/15$, where λ_g is the wavelength of the source in the disk. The wavelength of the source in vacuum is $3.3\mu\text{m}$ and the effective refractive index used to model the disks vertical structure is 3.3, so λ_d should be less than 67nm . For convenience, the mesh size in all three dimensions is set to 50nm . Figure 2 shows the graphical user interface view of a disk laser with an attached output waveguide.

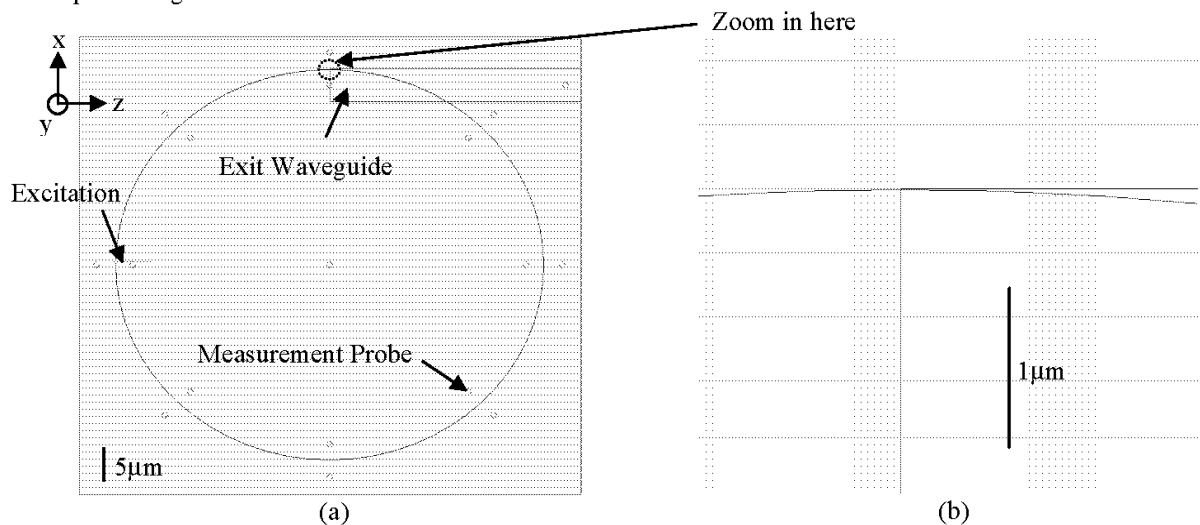


Figure 2. The GEMA viewer. The figure shows a disk laser with an exit waveguide. (a) Positions of the probes and excitation in relation to the disk. The marked measurement probe is the one used for all subsequent figures in this paper. (b) A magnified view of the.

The simulations in this paper use a Gaussian modulated sinewave excitation to model an idealized disk operating in whispering gallery mode. In the case described by figure 2, the electric field propagation direction will be both positive and negative in the z-direction. It is necessary to add a H_y component to force the field to travel in one direction. This is the simplest possible type of excitation that can be used. In future other more complex excitation techniques such as modal excitation [6] and random distributions of dipoles to model spontaneous emission will be studied.

3. RESULTS

Three disk geometries are studied in this paper to assess the effect of implementing an input or an output waveguide onto the disk. Other workers are undertaking similar studies in different types of disk resonators [7]. The in-house software allows probes to be placed inside and outside the disk and waveguide, the positions are shown in figure 1. Each one of these will measure the E-field in all three dimensions, and by performing a simple Fourier Transform on the field, the frequency response curve is attained. Plots of the total E-field magnitude in the x-z plane are shown in Fig. 3a–3c, along with their corresponding frequency response curve (Fig. 3d–3f).

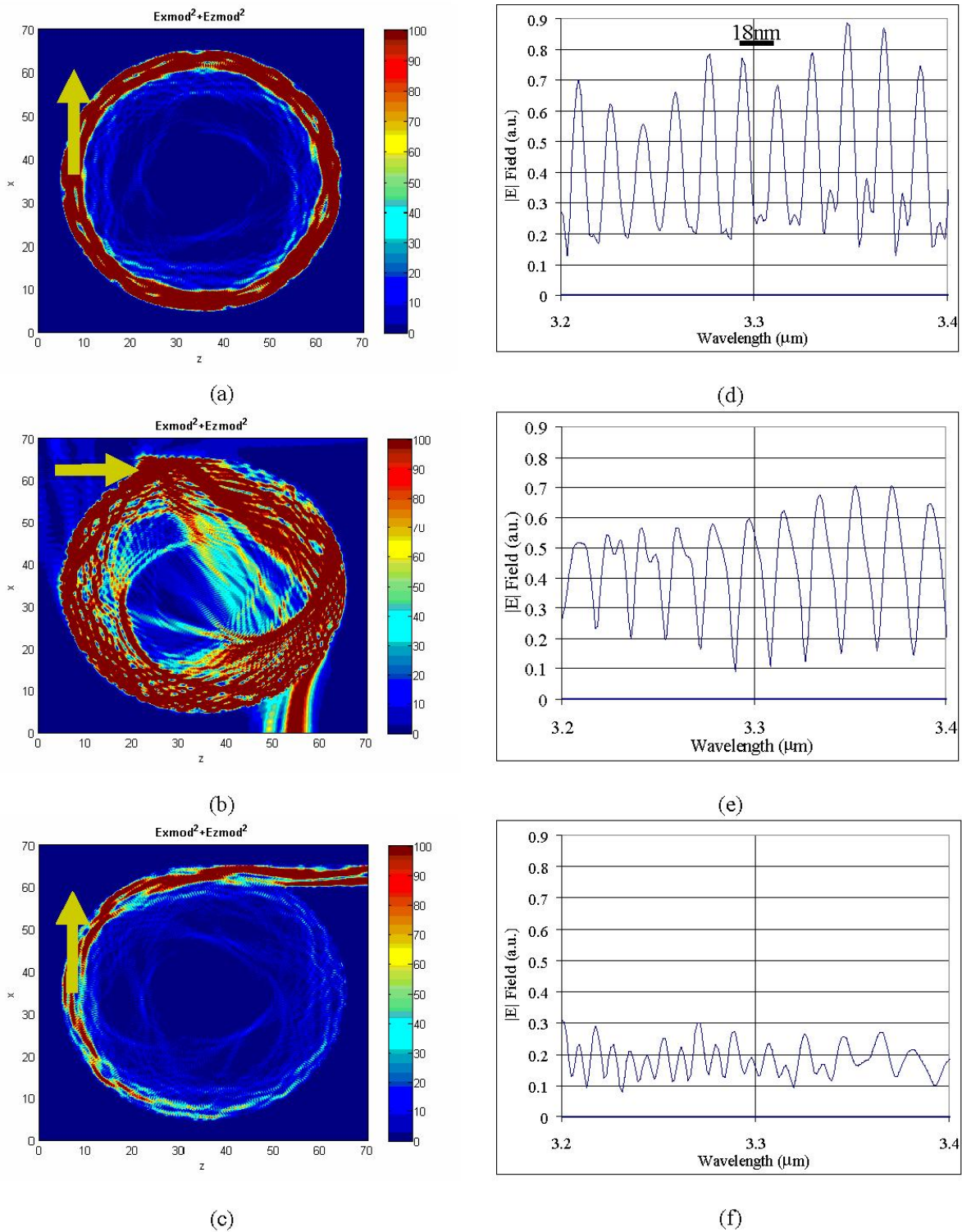


Figure 3. Three 60 μm diameter disk lasers operating in Whispering Gallery Mode (WGM). The direction of Gaussian excitation is denoted by the arrows. The three cases are (a) Internal excitation, (b) Excitation by input waveguide, and (c) Excitation direction same as output waveguide. Each disk laser has a corresponding frequency response curve (d-f) attained from the measurement probe.

Due to the small diameter of the disk, it is possible to resolve multiple radial modes in the spectrum. Taking the internal excitation case (Fig. 3a) we can observe the mode spacing at 3.3 μm to be approximately 18 nm. This observation is in good agreement with the expected mode spacing, which is related to the disk radius as follows [8]:

$$r = \frac{\lambda_0^2}{2\pi\Delta\lambda \left(n_{\text{eff}} - \lambda_0 \frac{dn}{d\lambda} \right)} \quad (1)$$

where r is the radius of the microdisk, λ_0 is the laser wavelength in the cavity, n_{eff} is the refractive index for the transverse optical mode, and $dn/d\lambda$ is the first-order dispersion in the material. However, at this stage we are assuming no material dispersion so after simplification and rearranging, $\Delta\lambda = 17.5$ nm. Figure 3a shows the idealized case when the excitation is placed within the ring and close to the edge of the ring so as to induce WG modes. The associated frequency response shows strongly resonant behaviour. In figure 3b, the excitation comes from an external waveguide directly attached to the ring. The Q of the resonances is seen to be reduced and it appears that strong emission is observed in an orthogonal direction to the input waveguide. Figure 3c shows the case of internal excitation in a clockwise direction with an output waveguide placed so as to collect the emitted light. It is seen that strong emission from the ring is observed, but Q factor of the resonances is severely reduced. This work will go onto to study the influence of connection geometry with the aim of maintaining high Q and high output efficiency

4. CONCLUSION

This paper has presented a 2D FDTD model of a disk resonator that could be used in a Mid IR laser and mode spacing has been shown to be in good agreement with a simple WGM model. The effect of a direct coupled waveguide has also been studied and shown to have a severe impact on resonator Q. We will go onto to study other coupling geometries including notched disk lasers and more conventional coupled output waveguide designs and compare the merits of each approach. These results will be compared with measurements from our project partners.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the DTI and the Photonics KTN, UK for funding this research.

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